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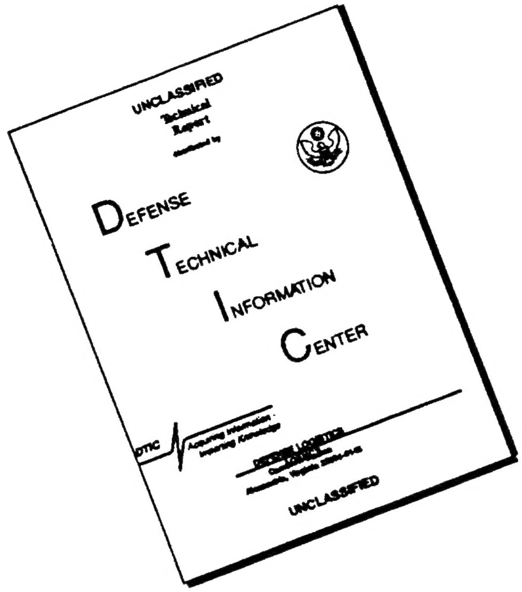

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Beam Combination with a Phased Laser Array

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Abstract: A phased laser array system based on many lower-power lasers can generate a high-power laser beam. Progress in the theory and experimental techniques of the phased laser array is summarized.

1. Introduction

With the ever-increasing need for high-power semiconductor laser devices and advancements in semiconductor technology, phased array technology for semiconductor laser devices has been widely developed [1], coupled with the emergence of commercialized phased array semiconductor laser devices [2]. In the past few years, following the proposals of the U.S. Strategic Defense Initiative, high hopes have been placed on attaining high-power laser output by making use of phased laser array technology.

Technically, a phased laser array system consists of a group of laser devices with well-matched frequency and phase, whose output beams combine coherently in the far field to make the system function like a single coherent light source. Even if an individual laser device in the array fails to provide high power, the array still can achieve a relatively high peak value of light intensity in the far field. Likewise, with mature technology, there are not as many problems in developing low-power laser devices as in constructing high-power laser devices, including optical element processing, medium non-uniformity, as well as intensified laser output, etc. Today, this system is expected to be applied to ground-based or air-based laser weapon systems.

At present, the phased laser array system is generally constructed with a main oscillator power amplifier structure (MOPA) [4] as seen in Fig. 1. Basically, the beam output from the main oscillator goes through a beam distributing element and then is input into several power amplifiers for amplification.

In this way, when noise is present (mainly fluctuations in the amplifier medium density), fluctuations of different amplifiers are not related to one another and furthermore, individual beams transmitting through different channels can cause phase errors, which eventually results in poor beam coherence and reductions in the peak value light intensity of the combined beam. Hence, whether a phased laser array system can realize a coherent beam combination depends chiefly on whether or not the frequencies of the various laser devices in the array can be locked, as well as whether phase matching among beams can be ensured.

At present, research in other countries is focused primarily on two kinds of phased laser array systems. One kind is designed to achieve phase matching among various beams through servo photoelectric techniques such as photoelectric detection and self-adaptive optics, called type A MOPA. The other kind is aims at phase matching among beams using non-linear optical phase conjugation, called type B MOPA. The paper gives an overview of research and development of these two systems.

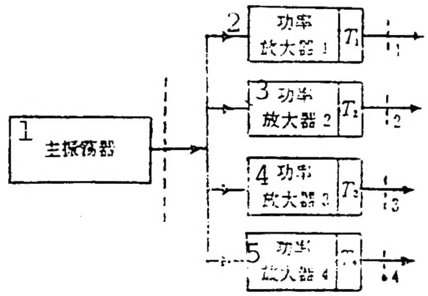

Fig. 1. Structural schematic diagram of MOPA

Key: 1. Main oscillator; 2. Power amplifier 1;
3. Power amplifier 2; 4. Power amplifier 3;
5. Power amplifier 4

2. Type A MOPA System

As early as the seventies, research was already underway on power extraction from the high-power HF/DF Laser Device (P>10 MW). Early studies suggested that to acquire a relatively high power output, the laser device was required to be custom-designed; for instance, the power was tailored to efficiently spread over multiple spectral lines. However, this somehow makes it hard for the wave fronts on various spectral lines to remain consistent with each other. As a result, a self-adaptive technique and sensing element were proposed for phase control among spectral lines.

At the same time, two power extraction approaches were worked out, namely ring-shaped non-stabilized cavity laser output [5,6] and main oscillator power amplification (hereinafter referred to as MOPA). Actual investigation shows that the former has the advantages of efficient power extraction and compact structure, but is inferior to MOPA in at least three aspects, i.e (1) it is extremely sensitive to maladjustment; (2) it is difficult to measure and control film quality, and (3) there is skip variation of spectral lines, competition among modes and an

abnormal chromatic dispersion effect. Therefore, research on MOPA has been at the forefront in recent years.

For example, some scientists such as A. W. Angelbeck et al. [7] originated an adjustable MOPA single spectral line chemical laser and its parallel optical cascade main oscillation power amplifier (POSW). Later, Warren developed this approach through using a multiple spectral-line chemical laser device. Nevertheless, although this latter method has overcome the foregoing three shortcomings, it has yet to achieve beam coherence and wavefront reconstruction of multiple spectral-line beams. Thus, C. P. Wang [8] advanced a new approach using a main oscillator and sub-oscillator array (hereinafter referred to as MOSOA) to allow phase control and beam combination. This method can effectively realize coherent beam wave array front reconstruction, beam control and focusing, as indicated in the block diagram in Fig. 2.

The whole setup consists of five parts, including main oscillator, sub-oscillators, coherent combination system, phase locking system and overall execution system. Generally, the main oscillator generates a lower-power beam which contains three reference beams at different wavelengths; and similarly, this beam can excite various sub-oscillators. The three spectral lines derived from the main oscillator are modulated (necessary for heterodyne detection) with different photoacoustic modulators using different modulation frequencies (hereinafter referred to as AD), and their phases are accurately controlled through the servo system and PZT. Still, by using the servo system and PZT, plus light amplification of the gain medium, various sub-oscillators, excited by the main oscillator incident ray, are allowed to have similar phases as the main oscillator and then output beams of the same phase through their common output mirror.

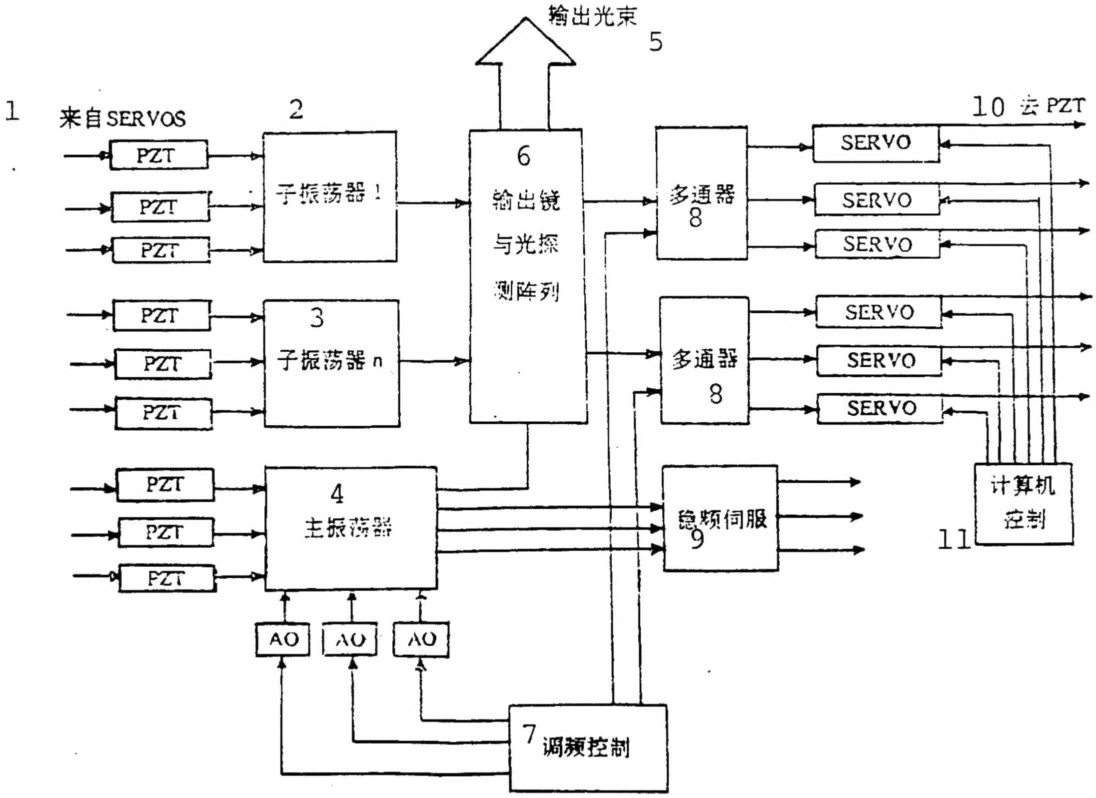

Fig. 2. Block diagram of MOSOA System

Key: 1. From servos; 2. Sub-oscillator I; 3. Sub-oscillator n; 4. Sub-oscillator; 5. Output beam; 6. Output mirror and light detection array; 7. Frequency modulation control; 8. Multichannel device; 9. Frequency stabilization servo; 10. To PZT; 11. Computer control

The servo system principle is that the electrical signal derived from the photoelectric detector is designed to go first through a multiple path beam distribution transmission line (beam distribution is based on different AD modulation frequencies), then to pass through the computer controlled phase detector and phase shift device, and finally, when it is amplified, its phase is controlled and adjusted by PZT (see Fig 3).

Once again, C. P. Wang et al. also designed a servo system used for a phase locking HF chemical laser device. This system can precisely measure stable phase differential value of various beams so as to achieve wave front resetting. The servo system

block diagram is shown in Fig 4.

In recent years, using the MOPA concept, J. M. Bernard et al. [10] accomplished phase locking for two continuous wave HF laser devices. The corresponding main oscillator power amplification experimental equipment and phase array setup are indicated in Fig. 5. Noticeably, the output power of each HF oscillator is 3 W, which can rise to 6 W after power amplification. By making use of the method of measuring interference fringe visibility, coherence of the two amplified beams was measured as approximately 90%.

The experiment shows that the brightness of the optical field following the far-field coherence can reach nearly four times as high as single beam brightness. But since brightness derived from the coherent beam combination is extremely sensitive to the optical distance of the two beams, normally, the measured beam combination brightness is only 2.5 times as much as single beam brightness.

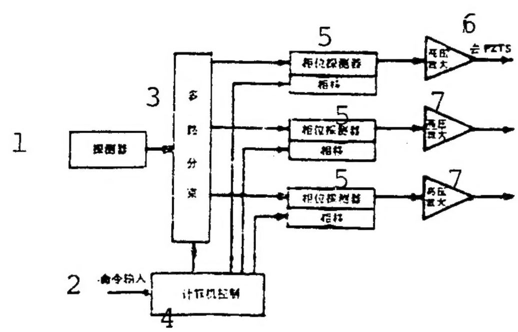

Fig 3 Block diagram of typical phase locking

Key; 1. Detector; 2. Instruction input;
3. Multi-path beam distribution;
4. Computer control; 5. Phase detector,
Phase shift; 6. High voltage amplification,
Remove PZTs; 7. High voltage amplification

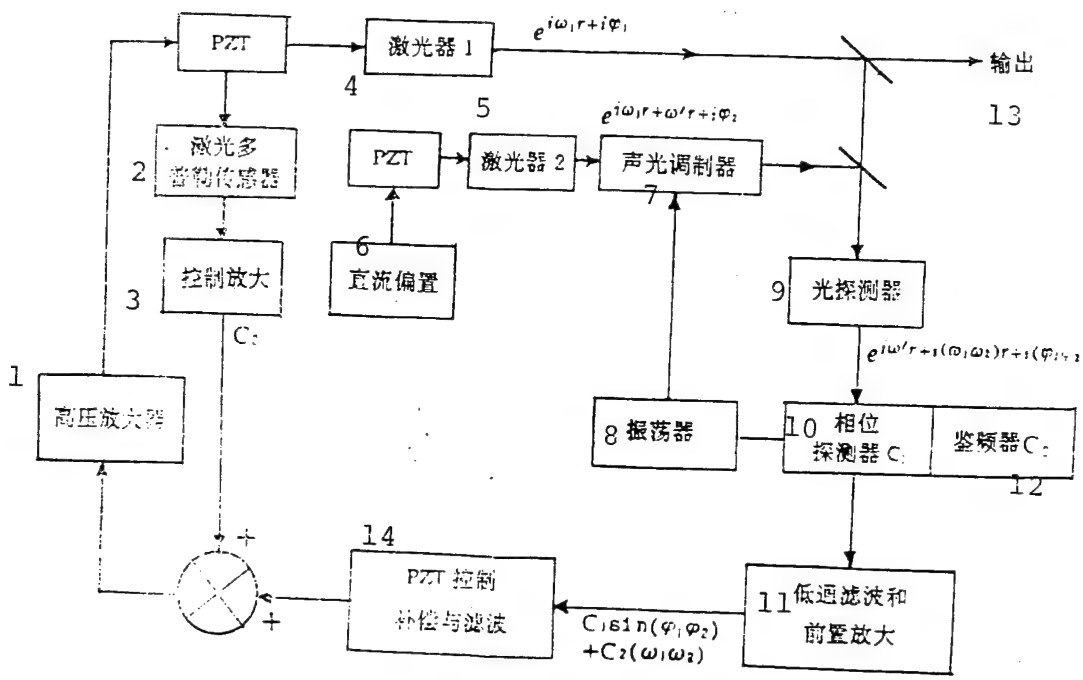

Fig. 4. Physical parts of servo system

Key: 1. High voltage amplification; 2. Laser doppler sensor; 3. Control amplification; 4. Laser device 1; 5. Laser device 2; 6. Direct current offset; 7. Photoacoustic modulator; 8, Oscillator; 9. Light detector; 10. Phase detector C; 11. Low-pass filtering and preposition amplification; 12 Frequency detector; 13. Output; 14 PZT control compensation and filtering

In addition to MOPA, Janet S. Fender et al. [11] also developed the "Optical Phase Control Telescope Array" (hereinafter referred to as OPTA) technology. This technology, originally born of the comprehensive radar bore diameter concept used in radio, was chiefly applied to astronomical telescopes. Before long, it was found to be totally applicable to a high-energy laser beam combination and therefore has drawn widespread interest. [12,13].

The heart of this technology is to realize precise measurement and control over phases in various combined sub-systems. The technology has become increasingly advanced and has been granted a patent in the United States [14]. Particularity

in the aspect of phase measurement, R. A. Carreras et al. [15] have disclosed the experimental results of phase control array obtained in the U. S. Air Force Weapons Laboratory. The experiment shows that using a standard instrument, $\lambda/10$ of the optical distance difference can be detected, and the absolute phase of the wave front can be precisely determined with multi-spectral lines of an Ar^+ laser. The experimental setup is shown in Fig. 6. In addition, the phase translational closed-loop bandwidth is 130 Hz, precision $\lambda/15$, tilt control bandwidth is 950 Hz, and precision 40 nrad. Interestingly, this experiment is the first to realize emission optics phase array. This setup, among other things, also enables swift beam direction switching, with a switching scope of 100 μrad, bandwidth 250 Hz, residual wave front error $\lambda/10$.

Also, it is necessary to provide a reference beam to determine and control various sub-system phases, for which, D. E. Elerath [16] put forward three different phase reference assumptions, namely, the remote sensing reference, fixed reference and floating reference. Moreover, a sensor that connects various sub-systems and a corresponding control system together forms a pivotal link in the realization of this technology.

3. B-Type MOPA System

Compared with the A-type MOPA system, which has been well studied and developed, the B-type MOPA system is an infant technology that has just emerged in recent years but which promises a broad range of applications. Unlike the A-type MOPA system, the B-type system, with non-linear optical phase conjugation technology to compensate phase distortion, can achieve phase matching among various beams.

The U.S. company TRW is reported to have worked out a

program exclusively for development of the phased laser array system (PLAS). Figure 7 is a proposed air-based PLAS block diagram [17] reported to the US Strategic Defense Initiative Organization (SDIO) by TRW.

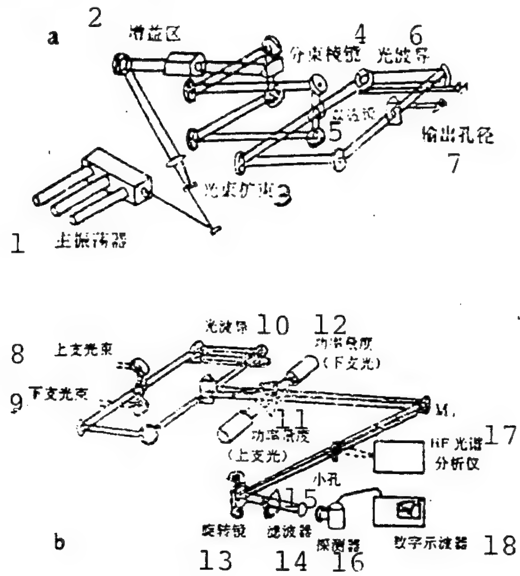

Fig. 5.

a—带放大器的主振荡器结构装置图

b—相控阵列系统结构图

a - Structural diagram of main oscillator with amplifier

Key: 1. Main oscillator; 2. Gain area; 3. Beam expansion; 4. Beam distribution prism; 5. Dual lens; 6. Optical waveguide; 7. Output bore diameter

b - Structure diagram of phase control array system

Key: 8. Upper beam; 9. Lower beam; 10. Optical waveguide; 11. Power density (upper beam); 12. Power density (lower beam); 13. Rotating mirror; 14. Filter; 15. Small hole; 16. Detector; 17. HF Spectrum analyzer; 18. Digital oscillometer

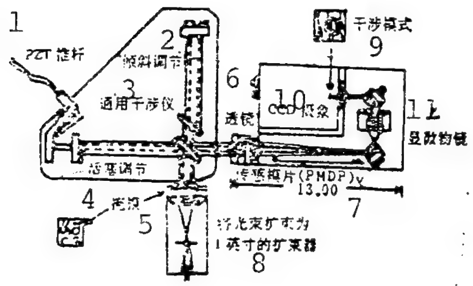

Fig. 6. Structural diagram of optical path

Key: 1. PZT push rod; 2. Tilting modulation; 3. Common interferometer; 4. Piston modulation; 5. Mask 6 lens; 7. Sensing film (PMDP); 8. Beam expansion device with a capacity of expanding to 1 inch; 9. Interference model 10 CCD camera 11. Microscope object glass

In 1988, G. J. Linford et al. from TRW constructed a practical high energy phased laser array system, the principle of which is shown in Fig. 8. Technically, this system is made of three sub-systems as follows:

1) Main Oscillator Sub-system

This system is designed to provide a relatively low energy, high quality reference beam with a linearly polarized single beam, which is input into the power amplifier. The frequency spectrum of the output beam from the main oscillator is required to match well the gain medium from the power amplifier in order to acquire satisfactory amplification.

2) Power Amplifier Sub-system

This system is tailored to perform multiple amplification over the output beam from the main oscillator so as to achieve a high-power laser output.

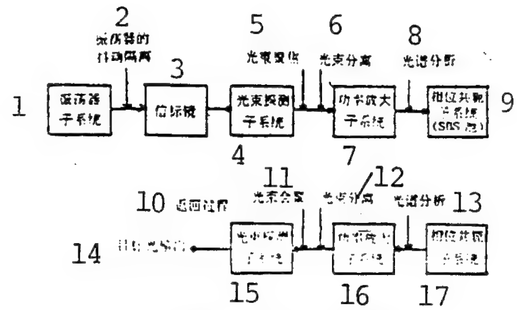

图7　PALS框图

Fig. 7. PALS block diagram

Key: 1. Oscillator subsystem; 2. Oscillator [illegible] deviation; 3. Beacon mirror; 4. Beam detection subsystem; 5. Beam focusing; 6. Beam split; 7. Power amplification subsystem; 8. Spectral analysis; 9. Phase conjugation subsystem; 10. Return process; 11. Beam convergence; 12. Beam split; 13. Spectral analysis; 14. [illegible]; 15. Beam detection subsystem; 16. Power amplification subsystem; 17. Phase conjugation subsystem

3) Phase Conjugation Sub-System

The phase conjugation sub-system contains an SBS phase conjugation pool, which is designed to ensure matching of frequency and phase among various beams reflected from this pool. To make this possible, this system focuses various beams into the SBS phase conjugation pool; at this point, the various beams, reflected from the SBS phase conjugation pool, not only accomplish phase conjugation, but also permit phase matching among various beams [19].

Figure 9 is a schematic diagram describing the high energy laser device phased array system.

4. Conclusion

In addition to the foregoing two laser device array systems, coherent beam combination also can be achieved using mutual coupling among laser resonance cavities. Figure 10 is a schematic diagram of an experimental system proposed by E. E. Palma and W. J. Fander to accomplish the beam coherence combination using double resonance cavity coupling of two CO_2 laser devices.

Coherence combination can also be realized by using beam diffraction features. S. Desilvestri et al. [21] presented an experimental system which is shown in Fig. 11. In this system, a piece of a multi-hole mask is inserted inside the Nd:YAG laser device cavity. When the interval among holes is relatively large, then beams output from different holes are not relative to each other; when the interval is small to a certain degree, beams from different holes can reach the coherent far-field combination due to the beam diffraction coupling effect.

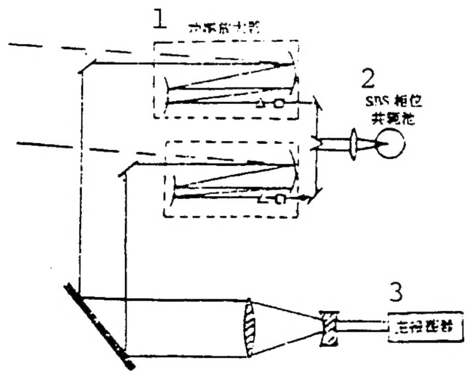

Fig. 8. Schematic diagram of system principle

1. Power amplifier; 2. SBS phase conjugation pool
3. Main oscillator

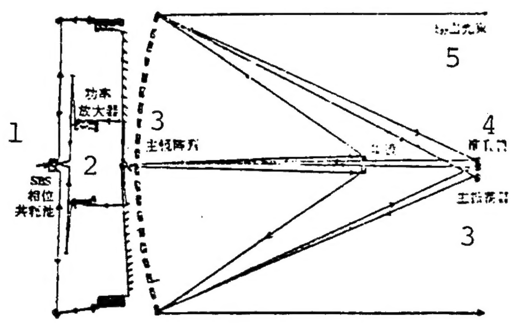

Fig. 9. Schematic diagram of high-energy phased array laser

Key: 1. SBS Phase conjugation pool; 2. Power amplification; 3. Main oscillator; 4. [illegible]; 5. Output beam

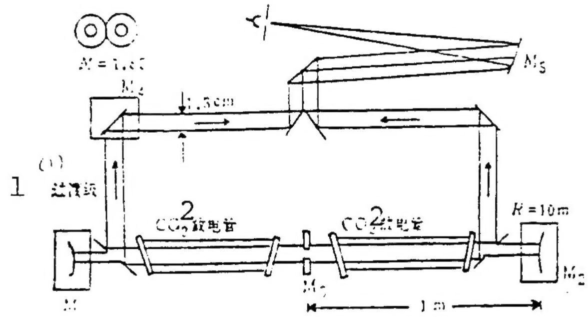

Fig. 10. Schematic diagram of resonance cavity coupling experimental system

Key: 1. Transition level; 2. CO_2 discharge tube

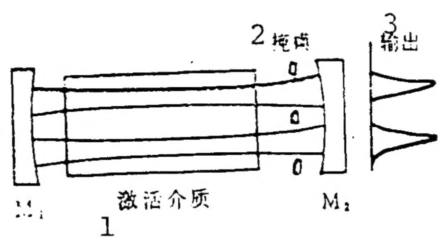

Fig. 11. Schematic diagram of mask coherent combination experimental principle

Key: 1. Activation medium; 2. Mask; 3. Output

In conclusion, phased array lasers as an active research field have been given more and more attention for which a large number of experiments and research have been carried out. So far, however, the semiconductor laser phased array has been the only one to be commercialized and applied. Other kinds of laser phased arrays still remain in the experimental stage, and still need further research. At present, phase locking has been achieved with dozens of semiconductor laser devices, with a continuous output power of phase the locking array reaching 1-10 W.

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